Heavy-ion induced desorption yields of amorphous carbon films bombarded with 4.2 MeV/u lead ions

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During the past decade, intense experimental studies on the heavy-ion induced molecular desorption were performed in several particle accelerator laboratories worldwide in order to understand and overcome large dynamic pressure rises caused by lost beam ions. Different target materials and various coatings were studied for desorption and mitigation techniques were applied to heavy-ion accelerators. For the upgrade of the CERN injector complex, a coating of the Super Proton Synchrotron (SPS) vacuum system with a thin film of amorphous carbon is under study to mitigate the electron cloud effect observed during SPS operation with the nominal proton beam for the Large Hadron Collider (LHC). Since the SPS is also part of the heavy-ion injector chain for LHC, dynamic vacuum studies of amorphous carbon films are important to determine their ion induced desorption yields. At the CERN Heavy Ion Accelerator (LINAC 3), carbon-coated accelerator-type stainless steel vacuum chambers were tested for desorption using 4.2 MeV/u Pb^{54+} ions. We describe the experimental setup and method, present the results for unbaked and baked films, and summarize surface characterizations such as secondary electron yield measurements, x-ray photoemission spectroscopy, and scanning electron microscopy studies. Finally, we present a high-energy scaling of lead-ion induced desorption yields from the MeV/u to GeV/u range.

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I. INTRODUCTION

The electron cloud (EC) effect [1] is one important limitation for existing and future high-intensity particle accelerators with positively charged beams of short bunch spacing, as for the Super Proton Synchrotron (SPS) and Large Hadron Collider (LHC) at CERN. During recent years, large efforts were put into the understanding and characterization of this phenomenon with the goal to mitigate the EC effect. At CERN, clearing electrodes [2] and surface coatings [3] are presently explored in order to find and apply a suitable electron cloud mitigation technique to the SPS vacuum system. The secondary electron yield (SEY) of the vacuum chamber surface is one of the critical parameters for the EC buildup, a SEY below 1.3 is needed for the SPS machine. A promising mitigation technique is the coating of beam pipes with a thin film of amorphous carbon which exhibits a SEY close to 1.0. In the specific case of the SPS, several dipole vacuum chambers have been coated with amorphous carbon and are presently installed in the machine in order to study their dynamic vacuum behavior with LHC-type proton beams. Since the SPS also accelerates heavy ions for the LHC, the heavy-ion loss-induced gas desorption is important to measure prior to the coating of the entire SPS vacuum system. For a first desorption test, the LINAC 3 experiment has been used to measure the dynamic vacuum properties of amorphous carbon coated stainless steel vacuum chambers bombarded with 4.2 MeV/u lead ions.

II. EXPERIMENTAL SETUP

A. Experimental system

The LINAC 3 heavy-ion induced desorption experiment has been employed to study the gas desorption of two amorphous carbon coated accelerator-type stainless steel vacuum chambers, which were bombarded under grazing angle impact with lead ions. The experimental setup and techniques used to measure the effective desorption yields and to quantify the desorbed gas composition have been described previously [4,5].

B. Carbon coating of chambers and samples

For the heavy-ion desorption study, two identically fabricated and cleaned 316LN stainless steel test vacuum chambers (1400 mm long, 145 mm inner diameter) were

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coated. The amorphous carbon film was deposited by DC magnetron sputtering in a vertical cylindrical configuration using a centered carbon cathode. The sputtering system, previously used for the TiZrV coatings of the long straight section vacuum chambers of the LHC, is described elsewhere [6]. Both LINAC 3 test chambers to be coated were assembled in series with two additional 500 mm long extension chambers of the same material and diameter. The extension chambers were equipped with various samples, which were used to characterize the carbon film properties in addition to the desorption measurements.

For the carbon film sputtering of the vacuum chamber assembly, neon was used as process gas at a pressure of 1×10^{-2} Torr. During the 24 h long sputtering process, with a power of about 1424 W ($I = 1.71$ A, $U = 833$ V) and a substrate temperature of 120°C, a film thickness of 510 nm was obtained. The end flanges of the LINAC 3 test chambers were both coated with identical parameters in a second run.

C. Experimental procedure

As described above, both amorphous carbon coated vacuum chambers were investigated and effective ion-induced desorption yields have been measured for a fixed impact angle of $\Theta = 89.2°$ (grazing angle) using 4.2 MeV/u Pb^{54+} ions. Most of the previous LINAC 3 ion desorption experiments were performed with test chambers which were baked *in situ* at 300°C. Therefore, chamber #1 was baked for 24 h at 300°C and served as comparison to our previous experiments. Vacuum chamber #2 was tested for desorption without baking the carbon-coated chamber. This is of particular interest since the SPS accelerator vacuum system cannot be baked. For the third experiment, the same chamber was *in situ* baked for 24 h at 150°C.

The pressure rise method [4] was applied to determine effective desorption yield η_{eff} (molecules/ion), given by

$$\eta_{\mathrm{eff}} = \frac{\Delta P \times S}{\dot{N}_{\mathrm{Pb}} \times k_B \times T}, \tag{1}$$

where ΔP is total pressure increase during continuous heavy-ion bombardment, S is the pumping speed in ℓ/s, $\dot{N}_{\mathrm{Pb}}$ is the number of impacting lead ions per second, k_{B} is the Boltzmann constant, and T is the temperature.

III. RESULTS

A. Desorption yield measurements of amorphous carbon

As described above, both amorphous carbon coated vacuum chambers were investigated and effective ion-induced desorption yields have been measured for a fixed impact angle of $\Theta = 89.2°$ using 4.2 MeV/u Pb^{54+} ions. Desorption yield results for vacuum chamber #1, obtained with the calibrated residual gas analyzer (RGA) and the Bayard-Alpert gauge (BAG), are displayed in Fig. 1. Heavy-ion induced gas desorption of 300°C baked amorphous carbon is dominated by CO, followed by CO_2, H_2, CH_4, and H_2O. As usual, the yield decreases with increasing projectile dose (ions/cm^2), which is attributed to the so-called "scrubbing effect." The shape of the scrubbing curve (change in slope) after about 5 hours of lead-ion bombardment, observed for all desorbed gases except CO, is neither a measurement artifact nor a change in projectile intensity and therefore remains unexplained at the moment. We find $\eta_{\mathrm{eff}} \approx 6.9 \times 10^5$ molecules/ion for the 300°C baked amorphous carbon film, which is a factor of about 35 higher than previously measured for bare 316LN stainless baked and tested under identical conditions.

The results obtained for chamber #2 are summarized in Fig. 2. Heavy-ion induced gas desorption of unbaked amorphous carbon is dominated by CO, followed by CO_2, H_2, H_2O, and CH_4. A 150°C bakeout of the carbon coating does not significantly change the overall picture. Although the quantity of all desorbed molecules is reduced, especially for water, CO still remains the dominant released gas. We find $\eta_{\mathrm{eff}} \approx 4.6 \times 10^6$ molecules/ion for the unbaked amorphous carbon film and $\eta_{\mathrm{eff}} \approx 2.2 \times 10^6$ molecules/ion for the baked (150°C) carbon coating.

It is worthwhile to mention that the desorption measurements of the unbaked and the 150°C baked carbon coatings had to be performed with a reduced lead-ion dose, a factor of about 4 and 5 less than for the 300°C baked carbon film. This turned out to be necessary because a very large pressure rise, measured at the beginning of the scrubbing run, triggered the vacuum interlock of the experimental setup. Consequently, the vacuum instrumentation, namely the BAG and the RGA, were automatically switched off

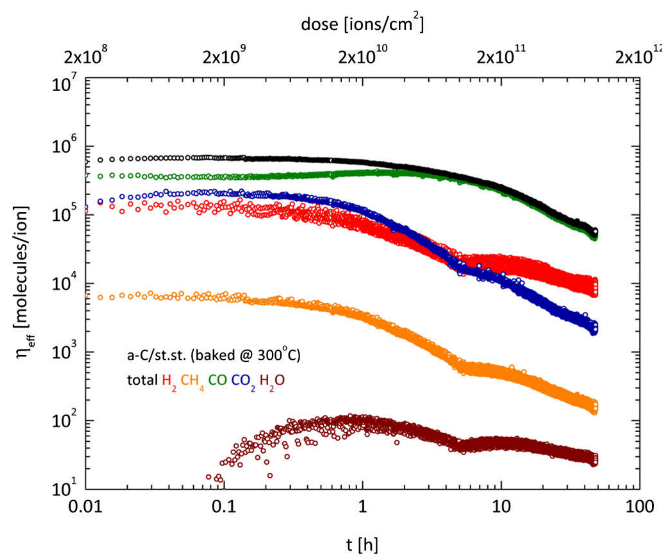

FIG. 1. Heavy-ion induced desorption yields measured for the 300°C baked amorphous carbon (a-C) film deposited onto stainless steel vacuum chamber #1. The target was continuously bombarded under $\Theta = 89.2°$ with 4.2 MeV/u Pb^{54+} ions.

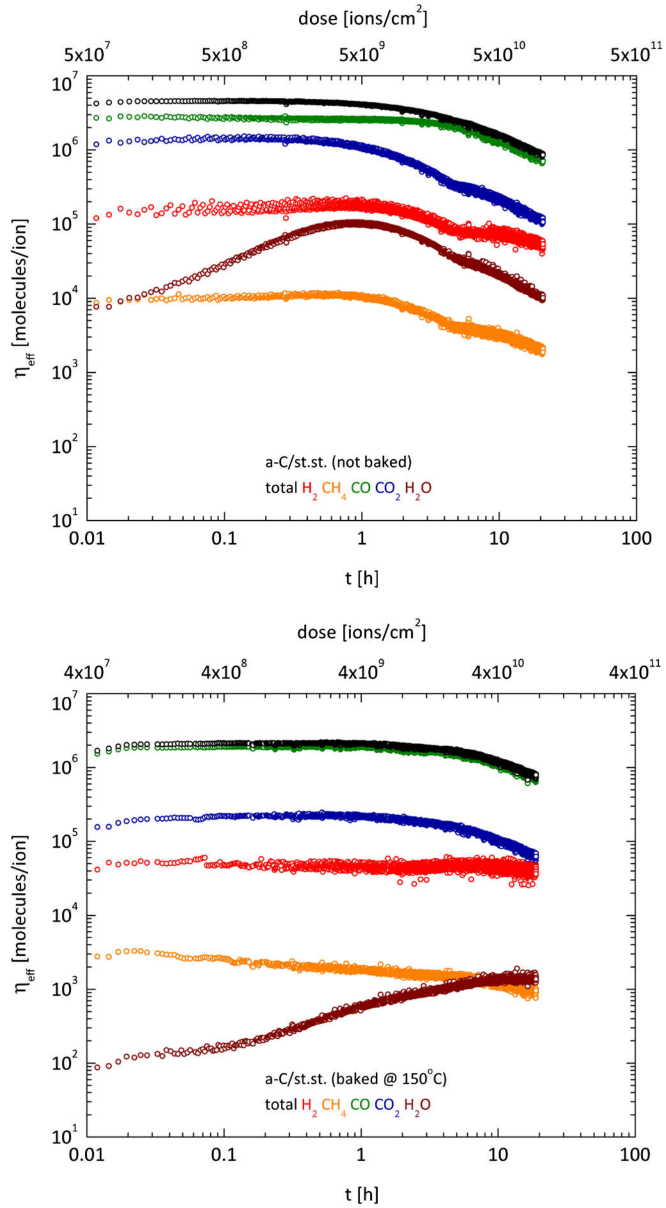

FIG. 2. Heavy-ion induced desorption yields measured for the unbaked (top) and 150°C baked (bottom) amorphous carbon (a-C) film deposited onto stainless steel vacuum chamber #2. Both targets were continuously bombarded under $\Theta = 89.2°$ with 4.2 MeV/u Pb^{54+} ions, note the 20% less ion flux for the experiment with the baked test chamber.

and the tests had to be stopped and restarted with a significantly reduced projectile flux. In the past, this effect had never been observed for any other bare or coated surface tested for desorption in the LINAC 3 test setup.

B. Desorption yield comparison with bare stainless steel

In the past many different types of bare metal surfaces (stainless steel, Cu, Al, Mo) and various coatings (Au, Ag, Pd, TiZrV) deposited onto stainless steel have been tested

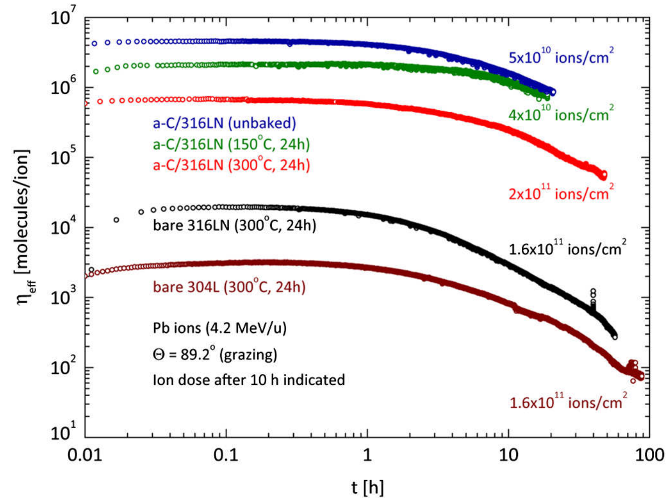

FIG. 3. Comparison of heavy-ion induced desorption yield measurements of amorphous carbon (a-C) films and bare stainless steel (316LN, 304L) surfaces continuously bombarded under $\Theta = 89.2°$ with 4.2 MeV/u lead ions.

for heavy-ion induced desorption with the LINAC 3 setup. A review of the obtained results can be found elsewhere [4]. Here, we want to compare the measured yields for amorphous carbon of this study with bare stainless steel; an overview is displayed in Fig. 3.

It is obvious that the measured amorphous carbon films show a much higher desorption yield than bare stainless steel. In comparison to 316LN stainless steel, baked at 300°C, the yield increase varies between a factor of 35 and 230 depending if the carbon coating was *in situ* baked (300°C) or not. We also note that the yield difference between baked (150°C) and unbaked carbon is quite small at the start of the scrubbing measurements and vanishes after about 20 h of bombardment with a dose of 4–5 $\times 10^{10}$ lead ions/cm^2.

IV. SURFACE CHARACTERIZATION

A. Secondary electron yield (SEY) results

As already mentioned before, both LINAC 3 test vacuum chambers were sputter coated with amorphous carbon together with various samples, which were used for surface analysis purposes. SEY measurements were performed with a dedicated instrument [7]. The experimental setup allows SEY measurements using low primary electron (PE) doses in order to avoid a conditioning of the sample surface. The total PE dose accumulated during the acquisition of one spectrum between 50 and 1700 eV was below 10^{-6} C/mm^2. The SEY versus PE energy curves for the amorphous carbon films tested in this study are summarized in Fig. 4.

The maximum SEY (δ_{max}) of the as-received carbon film is $\delta_{max} = 0.93$, the accuracy is estimated to ± 0.03. After 17 days of sample storage in air, δ_{max} increased to 0.98. A subsequent bakeout for 24 h at 300°C reduced the

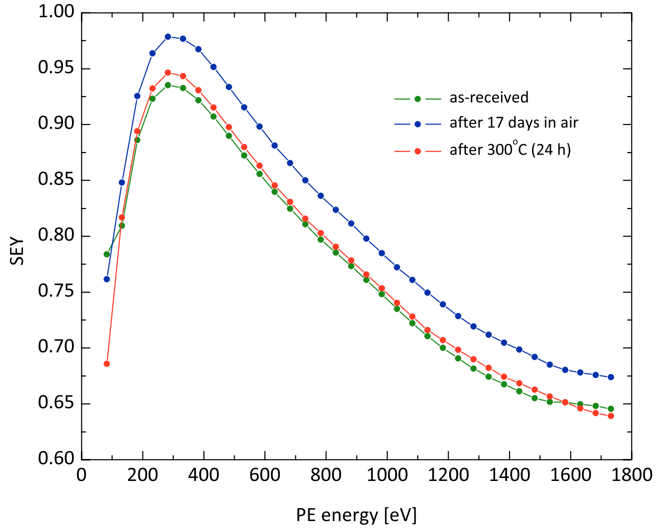

FIG. 4. SEY as a function of primary electron (PE) energy of amorphous carbon films tested for heavy-ion induced desorption. The samples were measured after film deposition (as received), after 17 days of air exposure, and after bakeout at 300°C (24 h).

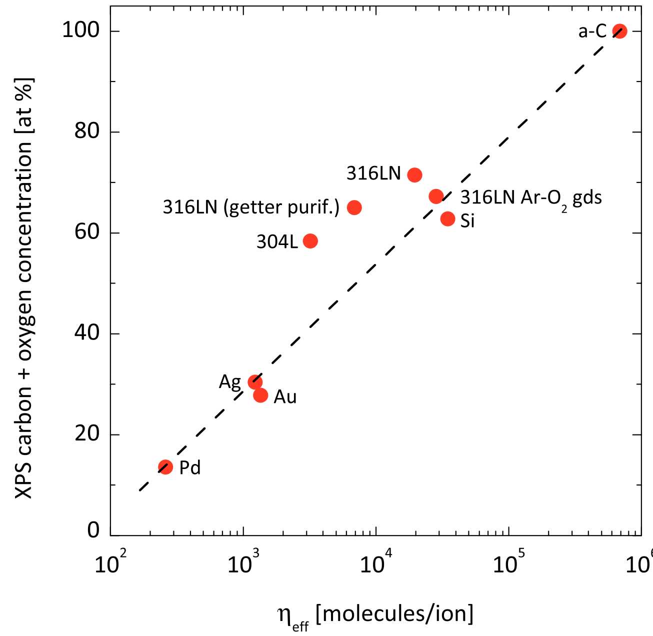

FIG. 5. Correlation of heavy-ion induced desorption yields, measured with accelerator-type vacuum chambers at LINAC 3, and the XPS carbon + oxygen surface-concentration of their corresponding samples, which were *in situ* investigated after a 300°C bakeout in UHV. Various coatings (Pd, Au, Ag, Si, a-C) on stainless steel substrates are compared to bare stainless steel (316LN, 304L) including surface cleaning methods as Ar-O_2 glow discharges [5] and getter purification. The dashed line only indicates the possible correlation.

yield to $\delta_{max} = 0.95$. The maximum yield is measured at primary electron energy of $E_{max} \approx 280$ eV. We conclude that the films tested for heavy-ion induced desorption are very well suited in terms of SEY for a future large scale application to the SPS vacuum system.

B. X-ray photoemission spectroscopy (XPS) analysis

The results obtained in previous studies have clearly shown that the heavy-ion induced desorption yield of the studied technical surfaces strongly depends on the surface properties of the targets. The amount of carbon and oxygen plays an important role since less surface adsorbates resulted in lower yield values [8]. Therefore, all samples were transferred under vacuum from the SEY instrument to the x-ray photoemission spectroscopy system. The objective of the XPS surface analysis was to determine the carbon and oxygen concentration on the amorphous carbon films before and after a 300°C bakeout in UHV. It was found that the concentration of carbon (85.4%) and oxygen (14.6%), measured before the bakeout, changed after heating for 24 h at 300°C to 92.1% (carbon) and 7.1% (oxygen).

The obtained XPS results for carbon are compared with other surfaces studied previously [5] and correlated with LINAC 3 desorption yield measurements of the corresponding vacuum chambers, see Fig. 5.

As can be seen from Fig. 5, the present study confirms the importance of having a low surface-concentration of carbon and oxygen to obtain a low heavy-ion desorption yield. This has been the case for the previously investigated noble metal coatings. In that respect, the measured high yields of our amorphous carbon films fit into the picture since the surface is covered with nearly 100% of carbon plus oxygen.

C. Scanning electron microscopy (SEM) analysis

In order to analyze the surface morphology of the sputter-coated amorphous carbon films tested for desorption in LINAC 3, different samples have been investigated with scanning electron microscopy. Typical pictures are shown in Fig. 6.

We find that our carbon films have a compact structure, a good adhesion to the stainless steel substrate, and that no loose particles can be found on their surface. All these aspects are judged as important film characteristics for any large scale application, for example the coating of the SPS accelerator vacuum system.

V. ENERGY SCALING OF THE DESORPTION YIELD

We have measured heavy-ion induced desorption yields of amorphous carbon films, coated onto accelerator-type stainless steel vacuum chambers, using 4.2 MeV/u Pb^{54+} ions impacting under grazing angle onto unbaked and baked surfaces. Within the CERN heavy-ion accelerator

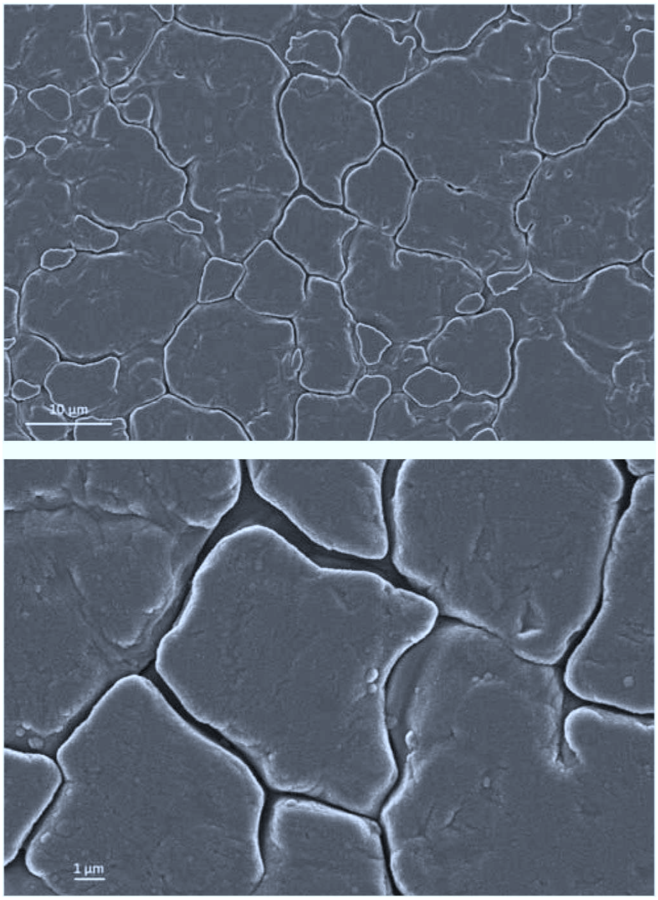

FIG. 6. Secondary electron image of an amorphous carbon thin film tested for heavy-ion induced desorption at LINAC 3. The 510-nm-thick sputter-coated film was deposited onto a stainless steel substrate, its grain structure is visible through the film.

chain, a projectile energy of 4.2 MeV/u is rather low in comparison to the ion energies obtained with the machines further downstream, i.e. in LEIR, PS, SPS, and LHC. The relevant energies are 72.2 MeV/u at LEIR extraction, 5.9 GeV/u at PS extraction and SPS injection, 176.4 GeV/u at SPS extraction, and 2.76 TeV/u at LHC top energy.

For a future carbon coating of beam pipes it is important to know how the measured heavy-ion induced desorption yields can be scaled to high projectile energies. No theory and no experimental data are available for the energy scaling of the desorption yield from MeV/u to the GeV/u and TeV/u energy regime. Here, we present an approach to obtain a first idea about lead heavy-ion induced desorption rates in the GeV/u energy range.

A. Energy loss

In the past, the energy scaling has been studied for perpendicular collisions of Ar and U ions with stainless steel in the energy range of 5–100 MeV/u [9] as well as for rather low-energy K ions at 0.002–0.025 MeV/u [10]. It was found that the desorption yield follows the electronic energy loss $(dE/dx)_{\mathrm{el}}$ of the projectile as follows:

$$\eta = k\left(\frac{dE}{dx}\right)^n_{\mathrm{el}}, \tag{2}$$

where k is a scaling factor and n varies between 2 and 3. The yield decreases for increasing ion energy above the Bragg maximum. For the above described experiments with argon and uranium ions, we found $k_{\mathrm{Ar}} = 1.7$, $k_U = 0.9$, $n_{\mathrm{Ar}} \approx 2.1$, and $n_U \approx 2.9$ with the electronic energy loss in units of $\mathrm{MeV\,mg^{-1}\,cm^2}$.

We have calculated the electronic and nuclear part of the energy loss of lead ions, impacting onto different accelerator-type target materials, using the SRIM code [11]. The results are shown in Fig. 7. As expected, the total energy loss is strongly dominated by the electronic part and the nuclear part can be neglected for the investigated energy regime in this study. The $(dE/dx)_{\mathrm{el}}$ of lead ions in carbon is highest among all materials studied.

B. SPS desorption yield

In order to extrapolate the LINAC 3 desorption yields to SPS energies, we have applied the energy scaling given by formula (2). We calculated the electronic energy loss of lead ions in carbon up to a projectile energy of 10 GeV/u for different values of n (1.5–3). This choice might look somewhat arbitrary but reflects the present uncertainty for the yield scaling, especially for the value of n, for which our previous experiments obtained $n \approx 2$–3. The obtained curves, shown in Fig. 8, are normalized in a way that the highest measured desorption yield ($\eta = 4.6 \times 10^6$ molecules/ion) of the unbaked amorphous carbon film fits with the dE/dx curve calculated for each value of n (see Fig. 8).

According to the described extrapolation, using the lead-ion energy-loss in carbon, we extrapolate for $n = 2.5$ a heavy-ion induced desorption yield of $\eta_{\mathrm{SPS}} \approx 1.6 \times 10^4$ molecules/ion at SPS injection energy of 5.9 GeV/u. As stated above, an important factor is the uncertainty of the n value in the used scaling law. A change from $n = 2.5$ to $n = 2.0$ results in an extrapolated yield of $\eta_{\mathrm{SPS}} \approx 4.9 \times 10^4$ molecules/ion while for $n = 3$ we obtain $\eta_{\mathrm{SPS}} \approx 5.1 \times 10^3$ molecules/ion. In case the high-energy yield scaling would be better described by $n = 1.5$, we predict $\eta_{\mathrm{SPS}} \approx 1.5 \times 10^5$ molecules/ion.

We have calculated the variation of the extrapolated desorption yield at 5.9 GeV/u as a function of the exponent n in formula (2). The results obtained for all tested amorphous carbon films, unbaked and baked at either 150°C or 300°C, are summarized in Fig. 9.

We also want to highlight that the extrapolated desorption yields might vary significantly; the yields certainly depend on the surface properties of the bombarded amorphous carbon film but also on the beam characteristics as the projectile impact angle and the lead-ion charge state,

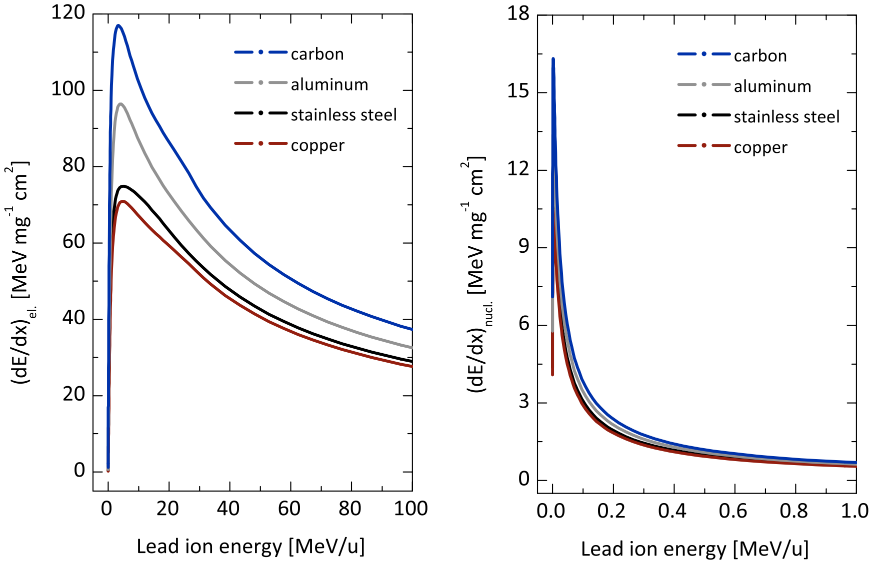

FIG. 7. Electronic (left) and nuclear (right) energy losses dE/dx calculated with SRIM for different lead-ion energies impacting onto carbon, aluminum, stainless steel, and copper targets.

which is 54+ in LINAC 3 and 82+ in the SPS. From SPS machine studies with lead ions, we know that the dominant beam-loss mechanism occurs during the so-called "rf capturing," which takes place at the start of the energy ramp [12]. Therefore, we are convinced that the "low-energy" SPS lead ions will contribute most to a beam-loss-induced pressure rise of carbon-coated SPS vacuum chambers.

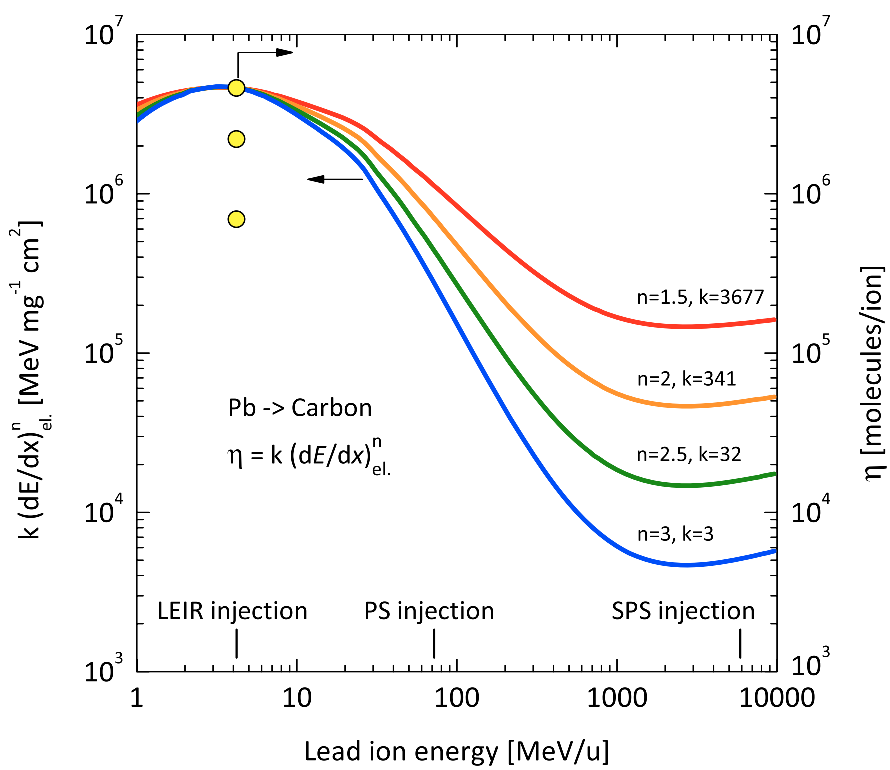

FIG. 8. Electronic energy loss $(dE/dx)^n_{\mathrm{el}}$ of lead ions impacting onto a carbon target (solid lines), calculated with SRIM as a function of ion energy and parameter n. The measured desorption yields (points) of the unbaked and baked amorphous carbon coated vacuum chambers, tested at 4.2 MeV/u, are also shown. The dE/dx curves are normalized to the highest desorption yield of $\eta = 4.6 \times 10^6$ molecules/ion, measured for the unbaked amorphous carbon film. The ion injection energies into LEIR, PS, and SPS are indicated.

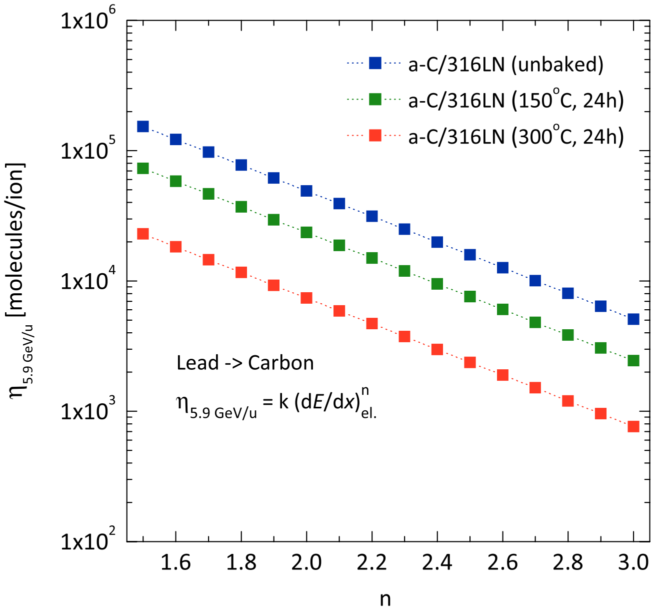

FIG. 9. Extrapolated high-energy lead-ion induced desorption yields $\eta_{5.9\,\mathrm{GeV/u}}$ measured at 4.2 MeV/u for unbaked and baked amorphous carbon films. The three curves show the yield variation as a function of n.

C. SPS pressure rise

In order to calculate potential SPS pressure rises induced by lead-ion losses onto amorphous carbon films, we have taken the extrapolated desorption yields $\eta_{5.9\,\mathrm{GeV/u}}$ which are displayed in Fig. 9. The pressure rise Δp is calculated with formula (1) assuming a pumping speed of $S_{\mathrm{SPS}} \approx 17\ \ell/\mathrm{s}$ and an ion-loss intensity equivalent to one SPS bunch, namely 1.25×10^8 ions. The resulting pressure rises at 5.9 GeV/u are $\Delta p \approx 1 \times 10^{-9}$ Torr for $\eta = 5 \times 10^3$ molecules/Pb^{82+} ion and $\Delta p \approx 4 \times 10^{-9}$ Torr for $\eta = 2 \times 10^5$ molecules/Pb^{82+} ion. Both calculated pressure rises would not pose any problem for the SPS beam lifetime and the operation of the machine.

VI. SUMMARY AND CONCLUSION

Heavy-ion induced desorption of sputter-coated amorphous carbon films coated onto accelerator-type stainless steel vacuum chambers and bombarded under $\Theta = 89.2°$ grazing incidence with 4.2 MeV/u Pb^{54+} ions has been studied. A yield of 4.6×10^6 molecules/ion was measured for unbaked carbon, *in situ* bakeouts in UHV only slightly reduced the yields by a factor of 1.8 after 150°C (24 h) and 6.7 after 300°C (24 h). The main contribution to the lead-ion induced pressure rise was given in all experiments by molecules (CO, CO_2) containing carbon and oxygen. A comparison with previous studies confirms the correlation between η and the amount of C and O present on the target surface. We want to mention that the measured yields might be correlated with the coating parameters. In particular, a purer carbon film with lower oxygen content could result in lower heavy-ion induced desorption.

In the "low-energy" range (5–100 MeV/u), the desorption yield of heavy ions was previously found to scale with the electronic energy loss $(dE/dx)^n_{\mathrm{el}}$ of the projectile. We have extended this approach and extrapolated yield values for lead ions from LINAC 3 energy of 4.2 MeV/u to the SPS injection energy of 5.9 GeV/u. We find that, depending on the scaling parameter n, the extrapolated yields for amorphous carbon are reduced by 2–3 orders of magnitude, namely about 10^3–10^4 molecules/Pb ion at 5.9 GeV/u. The studied 510-nm-thick films have a very low secondary electron yield (SEY < 1), a compact film structure, no loose particles on the surface, and good adhesion onto stainless steel substrates. We conclude that, despite the rather high desorption yield values measured at 4.2 MeV/u, amorphous carbon films are presently the most promising solution to mitigate the electron cloud phenomena in high-energy particle accelerators as the SPS.

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